New results of γ measurements in ADS and GLW-like decays at LHCb

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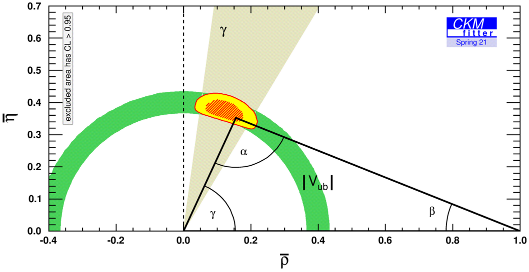
on behalf of the LHCb collaboration

CKM 2023

18th September 2023

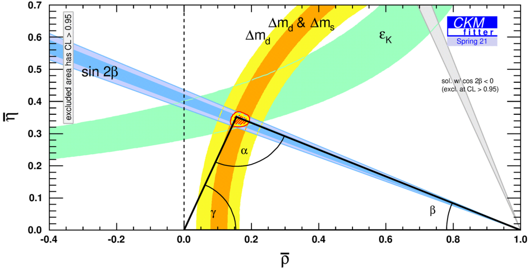
Why measure CKM γ?

Tree-Level Direct Measurement



$$\gamma = 72.1^{+5.4}_{-5.7}{}^\circ$$

Loop-Level Indirect Measurement



$$\gamma = 65.5^{+1.1}_{-2.7}{}^\circ$$

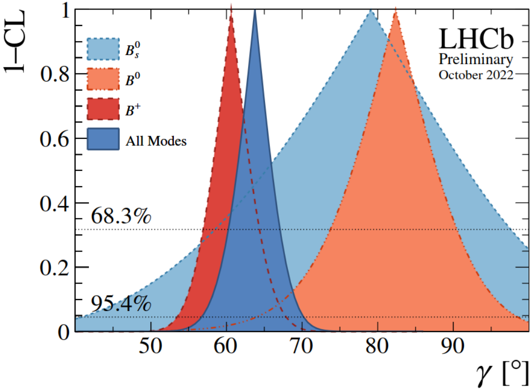
CKMFitter Spring 2021

- γ measurements have negligible theoretical uncertainty as hadronic parameters determined in data

Measuring γ at LHCb

LHCb γ Combination

$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$



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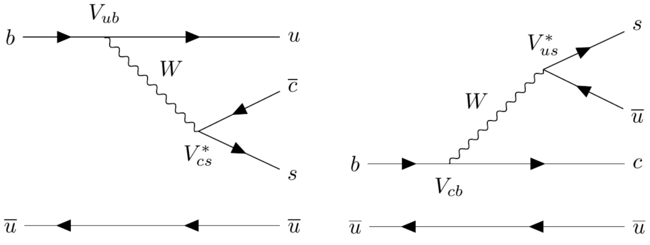
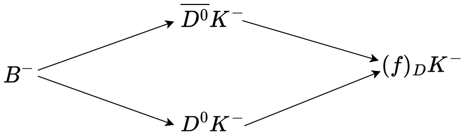
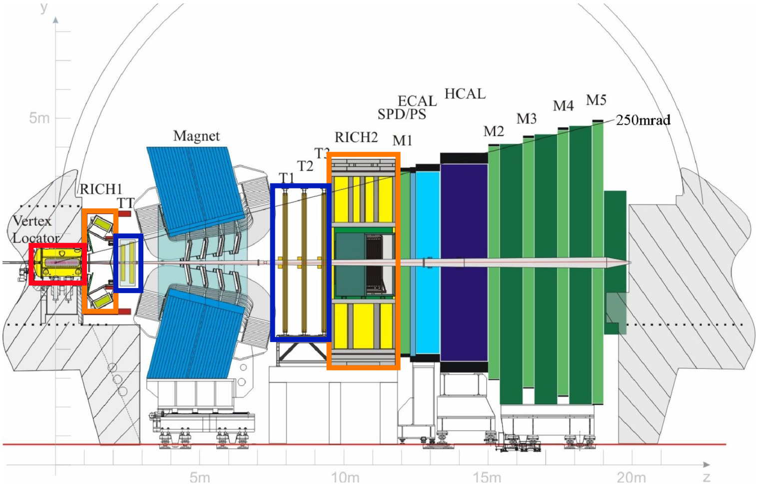
Measuring γ at LHCb

Interference of $b \to u\bar{c}s$ and $b \to c\bar{u}s$





Measuring γ at LHCb

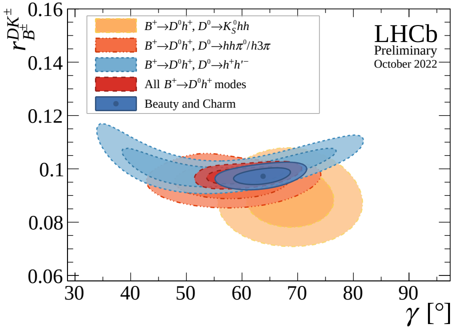


$B \to DX$ decays: select signal using displaced B and D vertices and PID

Using VELO, tracking system, and RICH detectors

Measuring γ at LHCb

Combining results from different final D states is important for improving sensitivity



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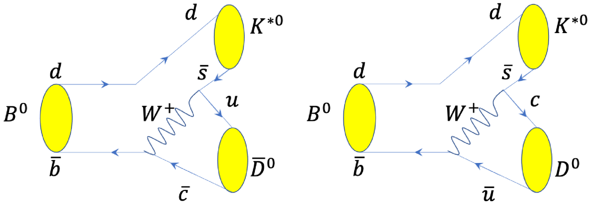
Focus of this talk: $D \to h^+h^-(h^+h^-)$ [$D \to K_S^0 h^+h^-$ will be covered tomorrow]

$B^{\pm}$ modes have high yields $\Rightarrow$ exhausting what can be done with them

Focus will be on a new result from B^0 mode today

New Results: $B^0 \to DK^{*0}(892)$

Measurement of γ using $B^0 \to DK^{*0}(892)$ with $K^{*0}(892) \to K^+\pi^-$



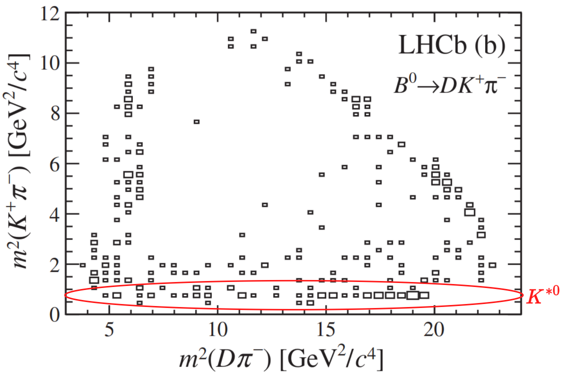
2 and 4-body D final states

Superseding LHCb measurements using Run 1 and 2015-2016 data[1] corresponding to 4.8fb^{-1}

K from K^{*0} tags flavour of B at decay $\Rightarrow$ time-integrated measurement with no $B^0 - \overline{B^0}$ mixing

[1] JHEP08(2019)041

Coherence Factor



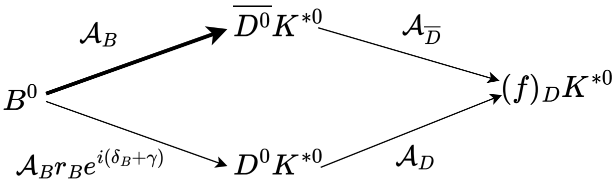
PhysRevD.93.112018

Coherence factor, κ, accounts for non-resonant contributions to the B decay

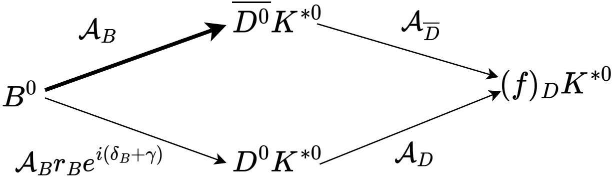
$\kappa = 0.958^{+0.005}_{-0.010}{}^{+0.002}_{-0.045}$ from Phys. Rev. D 93, 112018 $\Rightarrow$ using same K^{*0} selection

GLW-like Decays

- CP-eigenstates or modes with significant CP content so $\mathcal{A}_D \approx \mathcal{A}_{\overline{D}}$
- E.g. $D \to K^+K^-$, $D \to \pi^+\pi^-$, $D \to \pi^+\pi^-\pi^+\pi^-$
- r_B and δ_B are ratio of B amplitudes and strong phase difference between them
- Interference and therefore sensitivity to $\gamma \propto r_B$
- For $B^0 \to DK^{*0}$: $r_B \approx 25\%$



GLW-like Decays



$$R_{CP} = \frac{\Gamma(B^0 \to [h^+h^-]_D K^{*0}) + \Gamma(\overline{B^0} \to [h^+h^-]_D \overline{K^{*0}})}{\Gamma(B^0 \to [K^-\pi^+]_D K^{*0}) + \Gamma(\overline{B^0} \to [K^+\pi^-]_D \overline{K^{*0}})} \frac{\mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(D^0 \to h^+h^-)}$$

$$= \frac{1 + r_B^2 + 2r_B\kappa\cos(\delta_B)\cos(\gamma)}{1 + r_B^2 r_D^2 + 2r_B r_D \kappa\cos(\delta_B - \delta_D)\cos(\gamma)}$$

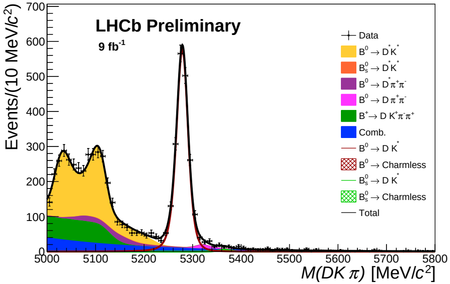
$$A_{CP} = \frac{\Gamma(B^0 \to [h^+h^-]_D K^{*0}) - \Gamma(\overline{B^0} \to [h^+h^-]_D \overline{K^{*0}})}{\Gamma(B^0 \to [h^+h^-]_D K^{*0}) + \Gamma(\overline{B^0} \to [h^+h^-]_D \overline{K^{*0}})} = \frac{2r_B\kappa\sin(\delta_B)\sin(\gamma)}{1 + r_B^2 + 2\kappa\cos(\delta_B)\cos(\gamma)}$$

Results: Control Mode $(D \to K\pi)$

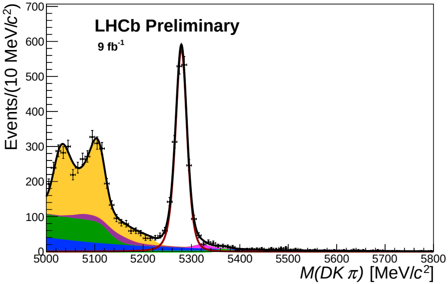
NEW!

Fit to $m(DK\pi)$ reconstructed mass for each flavour of each D final state

Signal peak shown by red line



$\overline{B^0}$



B^0

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$$A_{K\pi} = 0.033 \pm 0.017 \pm 0.015$$

Asymmetry Corrections

Ideally asymmetry only due to interference but also from:

Production Asymmetry

- Determined in Phys. Lett. B774 (2017) 139: $A_{\text{prod}} = (-8 \pm 5) \times 10^{-3}$

Detection Asymmetry

- Use difference in detection asymmetries for kaons and pions
- Estimated from calibration data: $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$
- Weighted to match signal kinematic distributions: $A_{\text{det}} = (-9.8 \pm 5.5) \times 10^{-3}$

Efficiency Corrections

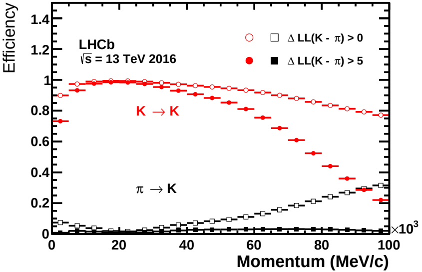
Most efficiencies cancel since CP observables are ratios

Selection Efficiencies

- Apply selection to simulation to determine efficiencies

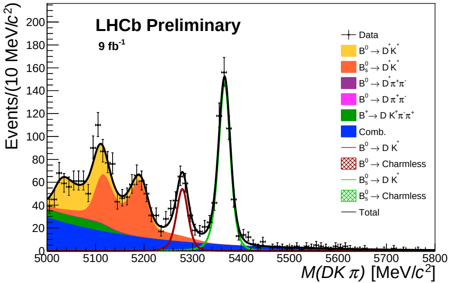
Charge-dependent PID efficiencies

- Estimated with calibration data for kaons and pions from D^* decays
- Weighted to match kinematics of signal decays in simulation

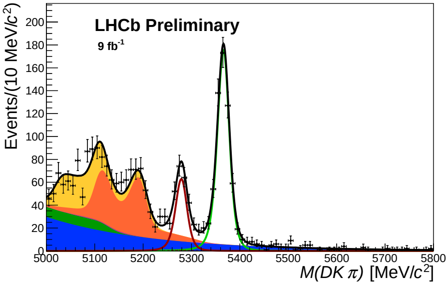


Results: GLW Mode $(D \to KK)$

NEW!



$\overline{B^0}$



B^0

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Green peak is $B_s \to DK^{*0}$ background, orange is partially reconstructed $B_s \to D^* K^{*0}$

$B_s \to DK^{*0}$ is a useful background for cross-checks since negligible interference

$$A_{CP}^{KK} = -0.047 \pm 0.063 \pm 0.015$$

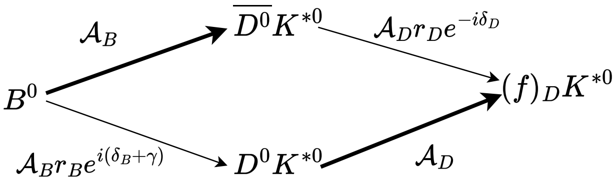
Small asymmetry

$$R_{CP}^{KK} = 0.817 \pm 0.057 \pm 0.017$$

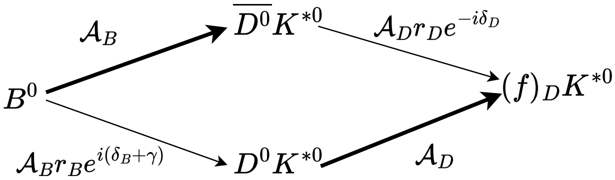
R close to 1 if effect of interference is small

ADS Decays

- Doubly-Cabibbo suppressed decays
- E.g. $D \to K^-\pi^+$, $D \to \pi^+K^-\pi^+\pi^+$
- r_D and δ_D are ratio of D amplitudes and strong phase difference between them
- Maximal interference due to similarly sized amplitudes



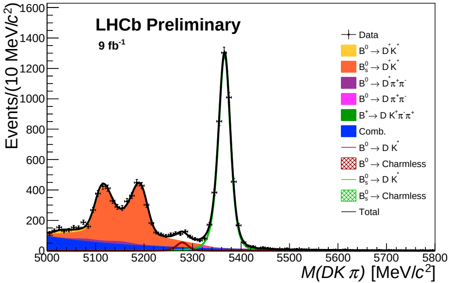
ADS Decays



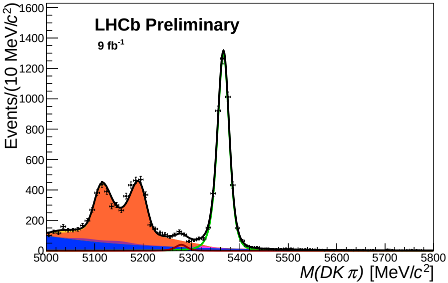
$$R^{+}_{\pi K} = \frac{\Gamma(\overline{B^0} \to [\pi^+ K^-]_D \overline{K^{*0}})}{\Gamma(\overline{B^0} \to [K^+ \pi^-]_D \overline{K^{*0}})} = \frac{r_B^2 + r_D^2 + 2 r_B r_D \kappa \cos(\delta_B + \delta_D + \gamma)}{1 + r_B^2 r_D^2 + 2 r_B r_D \kappa \cos(\delta_B - \delta_D + \gamma)}$$

$$R^{-}_{\pi K} = \frac{\Gamma(B^0 \to [\pi^- K^+]_D K^{*0})}{\Gamma(B^0 \to [K^- \pi^+]_D K^{*0})} = \frac{r_B^2 + r_D^2 + 2 r_B r_D \kappa \cos(\delta_B + \delta_D - \gamma)}{1 + r_B^2 r_D^2 + 2 r_B r_D \kappa \cos(\delta_B - \delta_D - \gamma)}$$

Results: ADS Mode $(D \to \pi K)$ **NEW!**



$\overline{B^0}$



B^0

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$$R^{+}_{\pi K} = 0.069 \pm 0.013 \pm 0.005$$

$$R^{-}_{\pi K} = 0.093 \pm 0.013 \pm 0.005$$

Leading order: $R^{\pm} \approx r_B^2$. Large $R^{\pm}$ imply larger r_B and increased sensitivity to γ in GLW mode

Multi-body D decays

GLW mode: $D \to \pi\pi\pi\pi$

- 2-body modes: CP -eigenstates so the CP-even fraction, $F_+ = 1$
- $D \to \pi\pi\pi\pi$: significant CP-even fraction, $F_+ = 0.735 \pm 0.015 \pm 0.005$ (Phys. Rev. D 106, 092004)
- Alters CP observables. E.g.

$$A_{CP} = \frac{2r_B\kappa(2F_+ - 1)\sin(\delta_B)\sin(\gamma)}{1 + r_B^2 + 2r_B\kappa\cos(\delta_B)\cos(\gamma)}$$

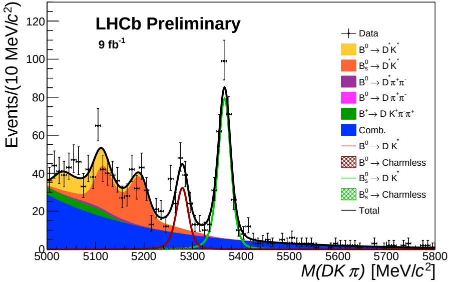
ADS mode: $D \to \pi K\pi\pi$

- Decay rates include coherence factor, $R_{K3\pi} = 0.44^{+0.10}_{-0.09}$ from JHEP05(2021)164
- Reduces interference by about factor 2 due to intermediate resonances in D decay
- E.g.

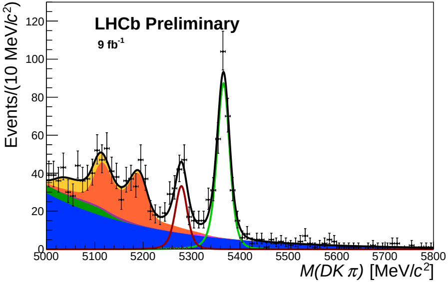
$$\Gamma(B^0 \to [K^+\pi^-\pi^+\pi^-]_D K^{*0}) \propto r_B^2 + r_D^2 + 2r_B r_D \kappa R_{K3\pi}\cos(\delta_B + \delta_D - \gamma)$$

Results: GLW Mode $(D \to \pi\pi\pi\pi)$

NEW!



$\overline{B^0}$



B^0

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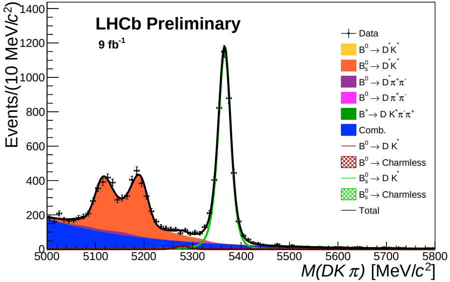
$$R_{CP}^{4\pi} = 0.882 \pm 0.086 \pm 0.033$$

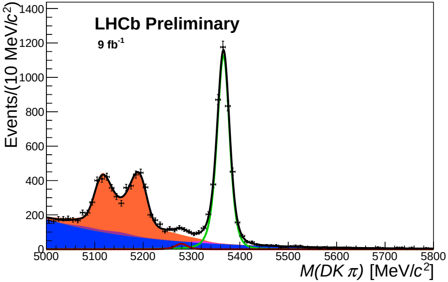
$$A_{CP}^{4\pi} = 0.014 \pm 0.087 \pm 0.016$$

Results: ADS Mode $(D \to \pi K \pi\pi)$

NEW!



$\overline{B^0}$



B^0

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$$R^{+}_{\pi K\pi\pi} = 0.060 \pm 0.014 \pm 0.005$$

$$R^{-}_{\pi K\pi\pi} = 0.038 \pm 0.014 \pm 0.005$$

Results: CP Observables

In general:

- Statistical uncertainties:
  - Improves by 60% compared to previous analysis (increased signal yield)

- Systematic uncertainties:
  - Dominant source in GLW asymmetries: asymmetry corrections
  - Dominant source in GLW ratios: branching fractions
  - No dominant source in ADS modes

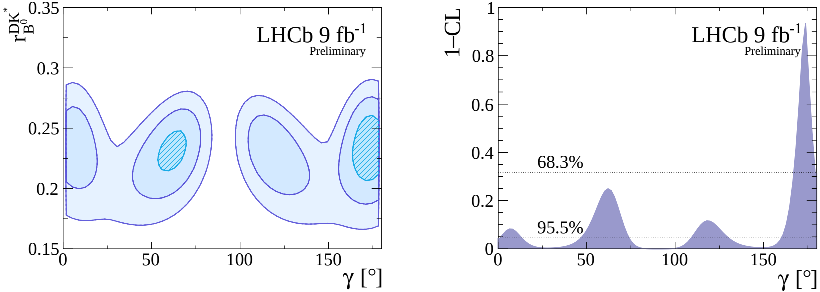
Analysis is statistically limited

Results: γ

NEW!

Interpret asymmetries and ratios in terms of physical observables[2]

Four-fold degeneracy: $(\gamma, \delta_B) \to (\delta_B, \gamma)$ or $(\pi - \gamma, \pi - \delta_B)$



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Preferred solution: $\gamma = 172 \pm 6^\circ$

Alternate solution (most consistent with world-average of direct measurements): $\gamma = (62 \pm 8)^\circ$

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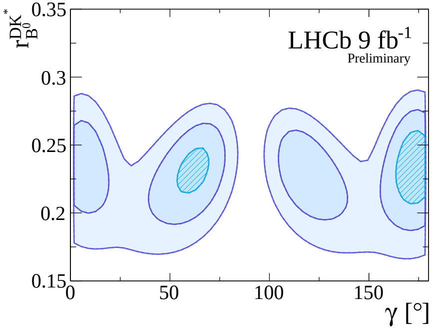
[2] JHEP12(2016)087

Results: γ

NEW!



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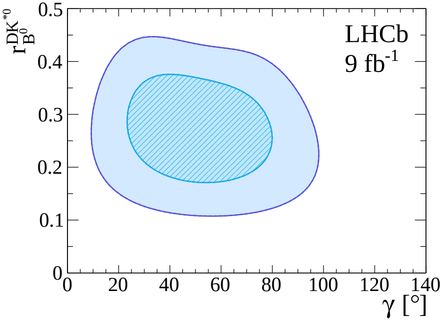


arxiv:2309.05514

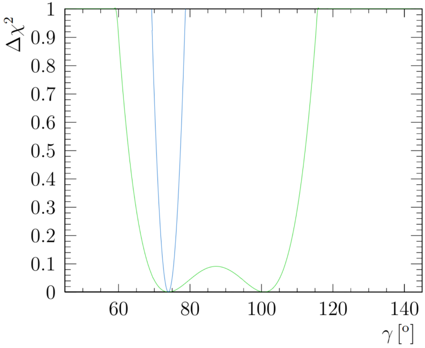
Results from $B^0 \to [K_S^0 h^+ h^-]_D K^{*0}$ will break the degeneracy

New Results: $B^{\pm} \to Dh^{\pm}$, $D \to K\pi\pi\pi$

Inclusive $D \to K\pi\pi\pi$ mode in $B^0 \to DK^{*0}$ analysis

In $B^{\pm} \to DK^{\pm}$ greater yields so can be more ambitious

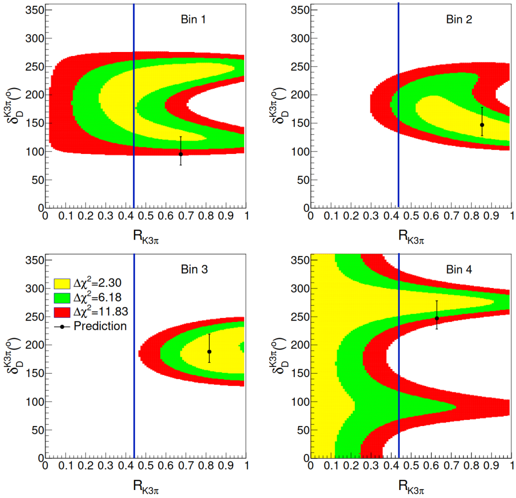
Sensitivity to γ improved by splitting phase space into bins where coherence factor is larger



From a sensitivity study: Phys. Lett. B 802 (2020) 135188

Green: 1 phase space bin Blue: 4 phase space bins

Binning Scheme

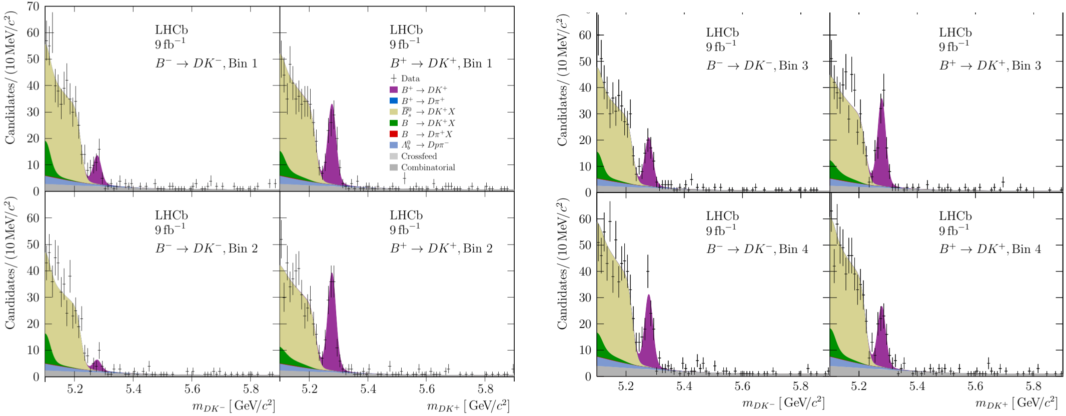


JHEP05(2021)164

- Proposed in Phys. Lett. B 802 (2020) 135188
- Contours from BESIII measurements
- Black data points are model predictions
- Blue lines show coherence with one bin: 0.44
- Bins 2 and 3: coherence > 0.44

Get more out of data by isolating regions where $R_{K3\pi}$ is larger

Results



JHEP07(2023)138

Bin 2 has largest CPV seen at LHCb!

$$\gamma = (54.8^{+6.0}_{-5.8}{}^{+0.6}_{-0.6}{}^{+6.7}_{-4.3})^\circ$$

Uncertainty from external inputs $>$ statistical uncertainty $\Rightarrow$ hope to see updates from BESIII to improve this

Conclusion

- LHCb has surpassed its target precision of 4° for γ
- Other analyses in the pipeline - not just ADS/GLW
- Also Run 3 results to look forward to
- Other LHCb γ talks this week:
  - Time-dependent measurements: Quentin Fuhring @ 9:20am tomorrow
  - $D \to K_S^0 h^+ h^-$ final states: Innes Mackay @ 9:40am tomorrow
  - γ uncertainties: Alex Gilman @ 5:55pm tomorrow

Thank You!